Effects of electric fields near power-transmission plant[1]

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Introduction

The transmission of electrical power by high voltage a.c. overhead lines is well established and some of the associated problems such as noise, interference with radio and television transmission, and the danger of flashover are well controlled. Reports of the occurrence of subjective complaints such as increased headache, lassitude, nausea and loss of libido amongst Russian substation workers were published in 1966 by Asanova & Rakov, and were followed by other reports from the USSR (Sazonova 1967, Korobkova *et al.* 1972). It was suggested that these symptoms were due to occupational exposure to electric fields in 500 kV and 765 kV substations. Some of the Soviet reports suggested that the workers experienced frequent small shocks and that these accounted for the symptoms.

Despite the reassurance given in reports by Western European and North American investigators (Kouwenhoven *et al.* 1967, Strumza 1970, Michaelson 1979) the suspicion remains in some quarters that currents or changes induced by high electric fields, even though they are imperceptible, can be damaging to the health of exposed persons.

In this paper reference will be made to previous reviews of the subject, concentrating particularly on those aspects which refer essentially to studies on humans.

Because of the widespread use of electricity in the modern domestic and industrial environment, any or all reports purporting to demonstrate that electric fields from power lines cause or aggravate ill health must be given serious consideration and be critically assessed. For this reason two recent reports of non-occupational exposure merit attention, namely that by Wertheimer & Leeper (1979) in which it was suggested that exposure to electromagnetic fields, as assessed by levels of domestic electric current concentration, was related to an increase in childhood cancer. The other by Perry *et al.* (1981) claimed to demonstrate an association between high voltage power lines and an increased incidence of suicide.

In addition to these reports, studies are under way in Sweden to investigate whether electric fields either *in vivo* or *in vitro* can cause chromosomal abnormalities in exposed persons or their offspring. The rationale for such an investigation and the study design itself are open to question and will be discussed.

Studies of human exposure

Since the primary concern is the possible deleterious effect on human health, it is through the study of human exposure that the significance of the various behavioural symptoms described in the literature will become apparent. The effects on experimental animals should be confined to confirming human findings or should attempt to explain mechanisms of action.

It was the study of complaints by Russian substation workers in the mid 1960s which triggered off the worldwide interest in high voltage field effects (Asanova & Rakov 1966). The symptoms complained of were nonspecific and included headache, fatigue and general gastrointestinal disturbances. These authors state that they gained the impression that changes in the cardiovascular system were encountered more frequently and were more marked in persons systematically subjected to electric fields (e.g. maintenance personnel), than those exposed sporadically (e.g. signalmen, substation attendants). None of these

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statements was supported by quantitative data. There is no detailed account of the incidence of disorders in relation to the duration of work in electric fields, nor is the incidence of similar symptoms in unexposed workers discussed. No objective basis is given for asserting that the observed disorders were in any way related to electric fields (Michaelson 1979).

Further reports of positive findings in men occupationally exposed to electric fields have been made by a number of Soviet authorities since this time (Sazanova 1967, Korobkova *et al.* 1972, Fillippov 1972). These tended to confirm the findings of Asanova & Rakov (1966) and reported loss of libido in addition to the nonspecific symptoms referable to the nervous, cardiovascular and digestive systems. They also reported various minor changes affecting blood pressure and heart rhythm. Finally, some changes in peripheral blood counts have been noted and ascribed to the action of electric fields. These include a slight leukocytosis mainly affecting the granulocytes, and a reticulocytosis, but these changes are minimal and fall within the normal range of physiological variability.

The fact that these disturbances were mainly found in subjects who had been exposed for long periods to strong fields, led the Soviet authors to put forward the idea of a threshold effect. After a study with volunteers exposed to fields of 0–30 kV/m, Fillippov (1972) reported that the haematological changes only occurred with fields of over 5 kV/m. He considered this to be the threshold above which it would be appropriate to limit either the length of exposure or the field stengths to which subjects were exposed.

On the other hand, Danilin *et al.* (1969) considered that these symptoms could have been caused by other environmental agents and they suggested kerosene and gasoline vapour which is frequently used by substation workers in Russia. It is also of interest to note that at a USA–Soviet symposium on extreme high voltage (EHV) a.c. power transmission, held in Tashkent, USSR, B M Savin *et al.* (1978 unpublished) expressed reservations about the validity of some of the earlier Soviet reports of adverse effects due to electric fields. This view was endorsed by Bourgsdorf (1980) at the 1980 CIGRE (Conférence Internationale des Grands Réseaux à Haute Tension) conference in Paris who stated that operational experience with 750 kV lines confirmed that the expected dangerous biological effects of electric fields had been over-estimated.

Most of the research done in Europe and the USA has produced negative results. The first of these was by Kouwenhoven *et al.* (1967) and Singewald *et al.* (1973) who studied ten linesmen over a 9 year period. Body currents calculated for these men were at times as great as those to be expected from exposure in unperturbed fields of up to 25 kV/m. The medical tests were extensive and no abnormality ascribable to electric fields was found, although the number of subjects was too small for any but the most gross effects to emerge. There were no control subjects.

The only reports of symptoms apparently associated with electric fields in Western Europe are those of Fole (1973) and Fole & Dutrus (1974). They reported observations on three workers transferred from 200 kV to 400 kV substations who complained of vertigo, visual disturbances, nausea and lassitude. In the later paper six subjects were exposed to fields of 15 kV/m for several hours and two subjects complained of loss of strength 'in the body', and changes in blood pressure and pulse rate were recorded. The brevity of these studies, the lack of controls, and the failure to confirm or substantiate any direct connection between the observed symptoms and the electric fields suggest that these reports are of doubtful validity.

In a study of families of Electricité de France employees, Strumza (1970) reported on a four-year investigation of 70 men, 65 women and 132 children living within 25 metres of 200 and 400 kV lines. His control group consisted of 74 men, 64 women and 120 children living more than 125 metres from lines. He failed to discover any difference on the basis of medical records, frequency of visits to family doctors, or expenditure on pharmaceutical prescriptions.

Occupational health surveys

Four major health surveys of occupationally exposed persons have been undertaken in the past five years. Malboysson (1976) studied a group of 84 substation workers and 76 linesmen in Spain and compared these with 94 linesmen working on low voltage systems. The men

were examined over a four-year period by questionnaire, medical history, and medical, haematological and retinal examinations. Biochemical tests consisted of blood glucose, serum cholesterol, triglycerides, urea and uric acid. The linesmen in both groups showed less sickness absence than the substation workers but there were no apparent adverse effects due to work in electric fields. No exposure measurements were taken and the data were not statistically analysed.

Roberge (1976) studied 56 maintenance workers employed in 735 kV substations in Quebec; they were exposed to fields of up to 15 kV/m over a 4½ year period. There were no controls and the men who volunteered were asked to complete a questionnaire. There were no gross effects noted on the health of these workers. It should be noted however that the exposure measurements were poor, duration was not quantified and there were no control groups for assessment of the questionnaire responses. Additionally, the men taking part were volunteers. Two important suggestions emerged from this study: firstly, 22 of the men taking part expressed fear and anxiety of electric shocks; secondly the ratio of sons to daughters was disproportionately high (17:3).

A second Canadian study was reported by Stopps & Janischewsky (1979) in which 30 high-voltage maintenance men from Ontario together with 30 employees matched for age and educational level but not exposed to electric fields were exhaustively studied in hospital. The investigation included EEG, ECG, blood biochemistry including tests of liver function, serum electrolytes; and complete physical and psychological assessment with psychometric and personality tests. At the time of examination the subjects were not identified as being exposed or control. The exposed group consisted of (*a*) 19 linesmen with an exposure experience calculated to be 7 kV/m hours per day – up to 8000 kV/m hours over 10 years; and (*b*) 11 substation workers with an average calculated exposure of 13 kV/m hours per day – up to 36 000 kV/m hours over 10 years.

It was concluded from this very exhaustive and thorough study that EHV work does not cause chronic ill health in substation staff in Ontario. Despite this it should be noted that the men taking part were all volunteers and represented a small number of total staff employed in these categories, the exposure expressed as kV/m hours was estimated and not measured, but some dosemeter checks were made. No acute effects were sought.

The fourth report is that of Knave *et al.* (1979) in which 53 workers in 400 kV switching stations in Sweden were studied in association with 53 employees working on low voltage systems: workers were matched by age, location and length of service, but not by educational level. Exposure details are incomplete in that they were assessed and not measured. Exposed and control groups were investigated thoroughly by questionnaire, EEG, ECG, medical and haematological examinations, and various psychometric tests. There was no evidence of gross effects from working in 400 kV substations. It is noteworthy that the exposed personnel performed significantly better than the control group, but this may have been due to the better educational level of the exposed group. It was also noted that the exposed group had significantly fewer sons than daughters compared with the control group. This latter finding is converse to that described by Roberge (1976). These findings have no significance epidemiologically and will be discussed later.

The European and American epidemiological studies are of a higher standard than the Russian reports, in that detailed information on all examinations and investigations are given. Even so, in some studies the medical examinations did not coincide with the period of exposure, the control groups were not always closely matched and the field strength and exposure were estimated and not measured. Despite this the evidence overwhelmingly suggests that high voltage (HV) fields do not give rise to chronic ill health.

Laboratory studies on human volunteers

The shortcomings of some of the studies detailed above emphasize the importance of laboratory tests such as those described by Hauf (1974) from the Technical University of Munich.

The advantage of laboratory studies is that exposure conditions are much more readily controlled and monitored, although long exposures present practical problems. Hauf (1974) exposed volunteers to fields ranging from 1–20 kV/m for periods of between 45 minutes and 5 hours. The experiments were not done double blind and it is possible that the subjects may have been able to perceive the fields in some instances. The main criteria used for comparisons were: (1) psychomotor tests – reaction times; (2) measurement of pulse rate, blood pressure, ECG and EEG; (3) peripheral blood counts (routine haematological tests); (4) serum electrolyte and blood biochemistry.

On the whole, these studies have produced negative results, apart from slight stimulation which delayed and reduced the effect of fatigue on reaction times. Slight changes were seen in the constituents of the blood, affecting the number of leukocytes, neutrophils and reticulocytes, comparable with those reported by the Soviet authors.

In order to provide a more precise definition of these slight changes, Hauf (1976) and his colleagues studied the effects of very low currents induced by low fields. These currents were close to the displacement currents which, from the physical point of view, are the only possible effect of exposure to an electric field. The negative results obtained from this new series of experiments have led Hauf to believe that the effects observed when subjects are exposed to an electric field are the effects of non-specific stimulation.

The work of Hauf (1976) and his colleagues accords with earlier Swedish studies by Johansson *et al.* (1973) who found that exposure to electric fields had no influence on performance in psychometric tests. The field strength was quoted as 100 kV/m 'at the head' and may be taken as indicating an unperturbed field strength of 5–10 kV/m.

T V Kalyada (1979 unpublished) reported mild reversible functional changes after a daily two-hour exposure to 10 kV/m over a period of twenty days. Krivova *et al.* (1977) found no physiological changes at 10 kV/m, but did identify some impairment of motor skills after exposure for two hours at 16 kV/m. In neither of these Soviet studies was there any mention of perception. However, both Soviet and Japanese studies agree that there are significant (although transitory) functional changes in people subjected to microshocks.

The general picture emerging is that no effects occur at fields below 10 kV/m, but that if people are exposed to fields of 10 kV/m or more for periods of a few hours per day, then transitory physiological changes may sometimes be observed. Even so, it is by no means demonstrated that it is the electric field *per se*, rather than apprehension or perception, which is the cause. It is very difficult in experiments of this kind to ensure that people do not perceive the electric field's presence through purely extraneous clues (Tucker & Schmitt 1978).

In a series of elegant experiments, Cabanes & Gary (1981) carried out tests of direct perception of electric fields by human beings in the high voltage laboratory of Électricité de France. By an arrangement of horizontal conductors placed at a height of nine metres above the ground, they produced an electric field which varied between 27 kV/m immediately under the conductors to 0·3 kV/m in other positions on the laboratory floor. Seventy-five volunteers submitted themselves to these field intensities in specified positions and described their impressions and sensations at these different points, not knowing what the field intensity was at each spot. From this survey it was possible to plot curves of perception, expressed in percentages of the sample of persons experiencing four different grades of sensation as a function of the field intensity. This survey demonstrated that perception of electric fields in human beings was a function of the mechanical stimulation of the hair which was brought about by electrostatic forces.

The sensitivity of perception of the bare forearm depended upon whether the forearm had been shaved. Removal of the hair markedly reduced the sensitivity of the forearm. The vibrations of the hair on the forearm were recorded by high speed photography; movements of 1 mm of hair were noted in fields of 50 kV/m.

A parallel series of experiments on animals confirmed these findings. Again using high speed photography, vibrations of as much as 1 cm of the whiskers of rats and mice in fields of 20–50 kV/m could actually be displayed, clearly indicating the extreme sensitivity of animals to the presence of electric fields (Cabanes & Gary 1981).

Non-occupationally exposed epidemiological studies

A relationship was claimed by Wertheimer & Leeper (1979) between childhood cancer and residence in houses with high current flow due to external electrical wiring configurations (e.g. transformers) in the vicinity of these houses, in comparison with a control group. The finding was strongest for children who had spent their entire lives at the same address and it appeared to the authors to be dose related. It did not seem to be an artefact of neighbourhood, street congestion, social class or family structure. They postulated that the correlation may have been due to the effects of current in the water pipes or of a.c. magnetic fields.

In a critique of this study, Miller (1980) commented that a dose-response relationship was suggested, but no doses (magnetic field intensities) for any addresses were given. Furthermore, Miller (1980) provides evidence that the household magnetic field from electrical appliances in the home would be far in excess of any contributions from electrical wiring configurations in the environment outside the house. A similar study carried out by Fulton *et al.* (1980) in Rhode Island failed to find any evidence to support the Wertheimer & Leeper hypothesis. Additional points of criticism of the Wertheimer & Leeper (1979) study are that the data were not collected blind and therefore there is a strong observer bias; and the cases were ascertained after death and therefore no account was taken of cancer cases still alive. It is vital in case control studies of this nature to ascertain whether birth or death addresses were used. It seemed from the published paper that both birth and death addresses were used, introducing a further strong bias in the data.

Another recent postulation has been the suggestion of a link between electromagnetic field exposure and suicide (Reichmanis *et al.* 1979). The report lacks any biological hypothesis. Suicide is an event and not a disease. It is frequently a symptom of a pre-existing psychotic illness and it is these diseases which need to be studied and classified. The paper is contradictory in its conclusions and is open to serious criticism for its incorrect use of epidemiological techniques.

Animal experimentation

Numerous experiments have been carried out on the exposure of animals to electric fields. Reported effects have included reduced water consumption in rats, reduced size of offspring and higher mortality in mice (Marino *et al.* 1976, Marino & Becker 1977), haematological changes in mice (Blanchi *et al.* 1973) and slower bone healing in rats (Marino *et al.* 1978). In all these experiments the animals were probably experiencing microshocks. Studies on bees in hives under power lines (Greenberg *et al.* 1979) suggest that the insects are affected only when they are subjected to microshocks on contact with the hive structure or with other insects.

At Battelle Pacific Northwest Laboratories, in the most careful and thorough work carried out so far, most of the physiological effects reported elsewhere have been sought, but not found (Phillips 1979). Some effects have, however, been confirmed in rats and mice exposed to fields up to 100 kV/m – fields which the animals could very probably perceive. Rats given the choice were found to spend more time out of fields greater than 90 kV/m than in them, and while in the fields were more active. At lower field strengths (25 and 50 kV/m) the rats spent the greater part of their time within the field zone.

Rats exposed from conception until eight days after birth showed slight behavioural differences relative to sham-exposed controls, although these differences had disappeared at 21 days after birth. Results of a conditioned-test response showed changes in the excitability of sympathetic ganglia in exposed rats and there were also changes in the numbers of red and white cells in the blood of exposed mice.

All the effects so far observed in the Battelle programme (Phillips 1979) are mild and within the normal range of variation for the animals concerned. A notable feature of the recent work is that as experimental techniques are refined so the number of observed effects has fallen.

Additionally, Le Comité Medical d'Electricité de France in collaboration with L'école Vétérinaire d'Alfortville have carried out a comprehensive series of experiments on rats, rabbits and mice to study various haematological and biochemical parameters following

exposure to controlled fields in the laboratory (Le Bars & Andre 1976). No significant abnormalities have been noted. Reference is made elsewhere to the studies carried out on the direct perception of fields in animals (Cabanes & Gary 1981). Similarly, studies on the biological effects of electric fields on mice, rats, rabbits and dogs have been carried out in Italy within the 1000 kV project operated by ENEL (Ente Nazionale per L'Energia Elettrica); the studies have been carried out by the Department of Physiology, University of Milan in collaboration with ENEL (Cerretelli *et al.* 1979). These studies were concerned with basic cardiovascular, haematological and biochemical parameters, and in addition growth fertility and teratogenic effects were also investigated as well as changes in resistance to induced infections. Again no significant abnormalities have been noted to date but the work is continuing.

No animal experiments have yet given clear indications of what might happen to people exposed to electric fields, one of the difficulties being that because of differences in size, shape and orientation, the electric fields and currents do not scale in any simple way, either in magnitude or in distribution over the body. Epidemiological surveys and experiments with human subjects are apparently essential if the question of whether subtle human health effects exist is to be satisfactorily resolved.

Discussion

Apart from the obvious hazard of accidental electrocution, no occupational disease pattern has been reliably reported from among high voltage workers. Uncomfortable or unpleasant subjective sensations such as induced voltage microshocks do occur in workers exposed to high voltage field radiance. It is of significance that as early as 1968 Krivova was speculating on the importance of exposure to microshocks in inducing symptoms in substation staff. Roberge (1976) described fear and anxiety of electric shocks amongst 22 of the 56 maintenance workers he investigated in Quebec. Takagi (1976) studied the response of 40 subjects under a 500 kV test line in Japan, and in fields of 5 kV/m and upwards the microshocks gave rise to definite unease amongst the participants. Clearly, therefore, in the design of any laboratory experiment the elimination of microshocks is a vital prerequisite.

A constant theme of Soviet work is that problems arise only in substations where voltages are 500 kV or more. Krivova *et al.* (1977) provide data on field strengths in such substations. Maximum levels are between 20 and 25 kV/m which is high by Western standards. The incidence of annoyance from shocks would, on the basis of American work, probably also be high.

An observation which has given rise to some speculation has been made in two reports: Roberge (1976) found an abnormally high male to female ratio of children born to high voltage field workers, and Knave (1981) reported an abnormally high proportion of female children. However, Knave (1981) emphasized that factors other than exposure to electric fields were probably responsible since the difference in the number of children was found to be present ten to fifteen years before the work in 400 kV stations began. The observation of a difference in the proportion of male and female children in small groups of people would be expected; in fact, even with large populations it is extremely unlikely to be unity. It therefore has no significance epidemiologically but is purely and simply an observation in a cross-sectional study.

Some investigators have found transient minor physiological changes in people after several hours of exposure to fields of 10 kV/m or more. None of these investigators has claimed that such changes are inconsistent with causes such as apprehension or perception of the presence of the field. Tests in laboratory conditions show that people normally do show transient physiological responses to stimulation by small electric shocks such as they might experience in high electric fields near a transmission plant. Experiments on animals have failed to confirm any pathological effects after extended exposure to fields of up to 100 kV/m.

Physiological responses in animals have been confirmed only at fields high enough for perception to be probable. The responses appear to be mild and the results have no clear implications concerning the health of people near transmission plants.

Research programmes are under way in several countries: the topics under investigation range from fundamental problems of the interaction of electromagnetic fields with living material, to direct attempts to identify specific medical effects – a particular example in the latter category being the continuing work in Sweden on possible chromosome damage and congenital malformations (Nordstrom & Birke 1979). This report included a retrospective study of the incidence of congenital malformations in the progeny of 542 male employees of the Swedish State Power Board and the incidence of chromosomal abnormalities in cultured lymphocytes from 20 workers employed in 400 kV substations.

A number of observations are relevant with regard to these studies. The increased frequency of malformations occurs evenly throughout the population studied, irrespective of whether they worked in 400 kV, 130–200 kV or 70 kV substations. The control group is composed of the same individuals before they were exposed. The whole study is therefore invalidated because the exposed and control group are not matched for age. Parental age is a most important factor in any study of congenital malformations.

With reference to the chromosome study, the criteria for the selection of the 20 exposed and 20 control persons are not defined. Furthermore it is assumed that persons who describe themselves as 'employees in occupation with 400 kV substations and transmission lines' are exposed to electric fields. There is evidence from recent UK studies that an assessment of exposure to electric fields may seriously overestimate exposure as measured by suitable monitoring instruments. Occupational hygiene practice requires personal monitoring of environmental factors in the working environment; fixed monitors with calculated exposures based on time give notoriously inaccurate results.

The question of whether people show any behavioural or physiological response to 50 Hz currents if those currents are totally unperceived is to be tackled in a joint experimental study by the Central Electricity Generating Board, the Medical Research Council and the Department of Occupational Health of Manchester University. Contact electrodes will be used to pass currents below the threshold of perception through volunteer subjects for several hours, the electrodes being disposed so that the current distribution within the body approximates to that which would be induced by external electric fields of unperturbed strengths up to 30 kV/m. A series of sensitive psychometric tests will be used to seek physiological responses to the presence of current. They will include tests of serial reaction time, visual search ability, and syntactic and semantic reasoning. Such tests are believed to provide the widest net that can be cast to catch a physiological change, while at the same time being well established and experimentally practicable. The subjects will be tested by application of double blind techniques.

A further question which may usefully be asked is whether some individuals may be especially predisposed to be affected by electric fields. The literature provides little guidance here, although it is known that individuals do vary in their ability to perceive fields (GE/EPRI 1978). Animal experiments planned at Battelle Pacific Northwest Laboratories will look specifically for correlations between behavioural and other responses (such as synaptic excitation) as a result of field exposure. One aim is to see whether sensitive individuals are also the most likely to show physiological effects. This work may provide some guidance for future investigational programmes on human beings.

In the studies reported by Cabanes & Gary (1981) on the stimulation of hair by electric fields, it was also apparent that there was a wide individual variation in the threshold of perception of the fields among the 75 persons taking part in the investigations.

At a more fundamental level, there is the question of what physical mechanisms mediate the interaction of power-frequency electric fields with the human body and what determines the thresholds of sensation, pain and muscle seizure. Various groups throughout the world are tackling this problem, but because of the complexity of human physiological make-up it seems unlikely, in the short term, that evidence will emerge from this direction to cast light on the question of whether exposure to electric fields is harmful to health. It seems sensible, therefore, to take the more direct approach of measuring the response of people to electric fields, while keeping a watch on theoretical and mechanistic investigations as they advance.

An immediate practical question that can be answered concerns the possible sensitivity of cardiac pacemakers to interference by transmission-plant electric fields. Extensive studies in the USA (Bridges & Frazier 1979) have shown that most pacemakers are unaffected by such fields. A few particularly sensitive types of pacemakers may revert in fields of 3 kV or more at 60 Hz to a mode of operation in which they stimulate the heart in competition with the natural heart impulses instead of in cooperation. Such reversion is not known to be harmful, but is considered by some cardiologists to be undesirable.

Preliminary information indicates that most pacemakers used in the UK are of the monopolar type, as opposed to the bipolar type more widely used in the USA. The monopolar type has more widely separated electrodes and will therefore pick up a larger interference voltage for a given body current. However, the lower power frequency used in Europe (50 Hz as opposed to 60 Hz in the USA) means that proportionally lower body currents will be induced for a given external field strength. This situation is under investigation by the Central Electricity Generating Board and the Cardiology Department at St Bartholomew's Hospital, London. The interference susceptibility of pacemakers used in the UK is being assessed by monitoring the performance of the more sensitive types while their wearers are exposed directly to electric fields.

A preliminary report was made in January 1982 (Butrous *et al.* 1982) which indicated that pacemakers of highly sophisticated performance can be designed to be totally insensitive. A number of pacemakers in common use will revert to the interference mode in quite low fields 3–4 kV/m.

Conclusions

A critical study of the physical and physiological phenomena associated with exposure of living organisms to electric fields, together with a review of the literature on the subject, was carried out by a group of experts from the industrially developed countries under the auspices of the World Health Organization in 1978 (see Bonnell *et al.* 1980). It was concluded that electric fields were harmless up to transmission voltages of 400 kV. They were also of the opinion that this view was valid for electric fields associated with transmission voltages of up to 800 kV.

This view remains, with the additional statement that the Soviet authorities also believe that their earlier assessments of this problem were pessimistic (Bourgsdorf 1980). Because of the overwhelming importance of the role of electricity in modern society, both industrially and domestically, further research work has been undertaken or planned in many countries, with strictly controlled conditions: but there is no new evidence to date to modify the view expressed by the World Health Organization group of experts in 1978.

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